Disruption to Transportation Systems Caused by Abandoned Mine Workings

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1. Introduction

The United Kingdom and major parts of Europe have a legacy of old mine workings. In large part of Britain over 25% of the total land surface area has been mined under often by multiple seams. Extraction methods in the past ranged from shallow bell pit systems, to pillar and stall (stoop and room) and finally to long wall extraction. Pillar and stall workings usually resulted in 60-75 % extraction but could have been greater as reworking of the pillars was practiced leading to near total extraction and early subsidence. The objective of bell pit working was to limit extraction to minimize the chance of collapse during mining activities. In time migration of the resultant voids could occur often taking many decades to reach the surface. The construction of the M1 motorway in England was disrupted by the presence of such voids close to the ground surface.

Pillar and stall workings often collapsed in the decades following extraction. There is growing evidence that some voids remain and recent cases of collapse have required extensive and expensive remedial works to strategic transport systems. The collapse of abandoned mine shafts, often the result of the deterioration of the "capping" is a particular hazard.

During the construction of the canal and railway transportation systems precautions against mining subsidence were unknown and remedial works were undertaken as necessary. Records show that in some locations this could be relatively frequent.

At the start of the construction of the motorway system in the United Kingdom in the early 1960's mining subsidence was acknowledged as a problem and a design concept was developed for the M1/M62 motorways based on historical records from the Yorkshire coalfield. The mining records were used to produce a prediction system suitable for design of motorway bridges and highway structures, Sims and Bridle (1966).

2. Risk and Hazards resulting from collapse of mine workings

Although the hazards posed by the collapse of old mine workings are recognized in respect of road networks, there are no established Risk Management strategies in general use. This is not so with rail networks were the potential disruption is significantly greater and the loss of life a major concern. Settlement of the track under a high speed train is a major hazard as derailment is

possible. The current standards set in the United Kingdom by Network Rail with respect to the hazards and risks arising from mineral extraction are laid down in:

Group Standard GC/RT5152 – "Mineral Extraction and Landfill – Managing the Risk"- Issue 2, December 1999 covering scope and procedures to:

- predict the effect of the underground mineral workings on the Infrastructure
- monitor the mineral workings
- maintain a register of all current underground mineral extraction sites which could affect the safety of train operators
- implement and maintain any works necessary to protect the safety of the operational infrastructure
- maintain a register of abandoned underground mineral workings which could affect the safety of train operators
- categorizing the mineral workings based on the assessed risk to the safety of train operators, taking into account known measures that have been implemented on abandonment of the mine
- implementing appropriate actions to manage the risk to train operators where such measures are justified on safety grounds
- maintain and update existing records of underground mineral extraction, including details of protection measures that have been implemented
- record all mining reports, site investigations, mitigating and remedial works carried out in assessing or reducing the risk from abandoned mineral workings

The Line Procedure (RT/CE/P/037) specifies the minimum requirements and actions to be taken to manage risk arising from subsidence damage and surface instability associated with mineral extraction. The Line Procedure includes an Action Plan for Proactive Remedial Works which gives priority to ancient mineral workings as follows:

- mine shafts
- adits
- shallow mine working

3. **Solutions to Mining Subsidence on High Speed Rail Lines**

3.1 Logging/Rafts/Ground Bridges

Historically logging was used to support rail lines subjected to mining subsidence and substantial lengths of the rail network in the U K were treated in this manner in the early 20th Century.

Logging provided support through shear resistance and bending in that it formed a crude bridge. The modern equivalent is a rigid reinforced concrete raft. For short lengths and relatively small surface discontinuities (crown holes) these can be simply supported. In the case of randomly occurring voids over a substantial area, a continuous raft is the modern equivalent which accommodates high speed trains. The raft can be supported on piles passing through the

workings and bearing on competent end bearing strata.   Alternatively the raft can be formed as a deep beam capable of spanning any potential crown hole. The selection between a piled raft and a deep beam should be based on a balance between the technical and economic benefits provided.

3.2   Artificial Rock Strata

The development of crown holes can be halted by the presence of competent rock strata above the mined zone, CIRIA (1984). Lean concrete (very low cement/aggregate ratio) has been used successfully on the M62 motorway to eliminate the need for piled foundations on motorway bridgeworks constructed in areas of mining subsidence. The concept is to create an artificial zone of competent material which halts the development of migrating voids.

3.3   Reinforced Soil (Mechanically Stabilized Earth)

An alternative method of constructing over voids is to use basal reinforcement beneath an embankment. Reinforced soil only works once the soil and reinforcement have been strained, i.e. deflection of the reinforcement is required to develop tensile force and the method cannot be identified with the logging technique of the past. The requirement of the reinforcement is to restrict the amount of deformation at the surface of the embankment. Design is based upon limit state principles and two limit states are considered. The ultimate limit state governs collapse modes of failure and the serviceability limit state governs deformation modes. For basal reinforced embankments spanning voids there are two ultimate limit states – rupture of the reinforcement and reinforcement bond failure, Figure 1(a).

One serviceability limit state exists – the maximum allowable differential deformation at the surface of the embankment, Figure 1(b), BS 8006: 1995. Because of the influence of the magnitude of reinforcement deformation on embankment surface deformations (d_s/D_s), fulfilling the serviceability limit state requirement poses the greater constraint. Parametric studies conducted in the UK, France and Germany have identified a number of controlling parameters relating to the use of basal reinforcement; these include:

i.   the ratio of the height of the embankment to the diameter of the void (H/D) - most subsidence voids is circular
ii.   the nature of the superficial soil properties at the surface on which the reinforcement is laid (weak soils result in the development of greater voids as there is limited edge support to the basal reinforcement
iii.   the stiffness and strength of the reinforcement used
iv.   the quality of the material forming the embankment

The effect of reinforcement stiffness on settlement criteria for different ratios of (H/D) and void diameters is shown in Figures 2 and 3. Both Figures 2 and 3 relate to polymeric reinforcement formed from high density polyethylene or polyester. Scrutiny of the surface differential

deformation (d_s/D_s) shows that these reinforcement materials have limited application in the case of shallow embankment and voids > 1.0m in diameter.

The surface differential settlement can be reduced by the use of very stiff reinforcement such as those provided by geosynthetics formed from aramid fiber or steel elements. Aramid reinforcement provides stiffness, J, in the range of 65,900 kN/m (short term) to 29,500 kN/m (long term). For comparison a steel mesh formed from 6mm diameter bars at 100mm centres has a stiffness value, J, of 60,000 kN/m. The relationship between the maximum tension in the reinforcement, T_{max}, and the ratio of the deflection of the reinforcement to the diameter of the void (crown hole) (d/D) is shown in Figure 4

3.4   Reinforced Soil – Piled Embankment

Piled embankments are used to reduce settlement of the track over soft/weak foundations and also to reduce settlement of the track adjacent to rigid structures such as bridge abutments and where embankment widening/run-in spurs are require. The piles can be formed as stone columns, cement stabilized stone columns or conventional piles. The stiffness of these piles ranges from modest to stiff (i.e. the use of conventional piles will result in the least settlement).

Piled embankments constitute a complex foundation interaction problem. Along the base of the embankment/new track are the incompressible pile caps interspersed between a compressible foundation soil. This difference in compressibility creates arching in the embankment fill between adjacent pile caps. The accurate assessment of the degree of arching and its effect on reinforcement loads is critical to the analysis. Reinforced piled embankments may be analyzed as two-dimensional (2D) or three-dimensional (3D) problems. If the piled foundation consists of a series of pile caps connected by beams then the problem should be analyzed by 2D methods, Low *et al* (1994). If the foundation consists of individual pile caps only, the problem should be analyzed by 3D means, Kempton *et al* (1998). The difference between 2D and a 3D analysis on reinforcement tension is shown in Figure 5.

4   Case Histories

A number of case histories relating to the construction of high speed trains over areas prone to subsidence have been published.

4.1   Germany Groebers, near Leipzig
A section of new high speed rail track (300 km/h) has recently been constructed in Germany at Groebers, near Leipzig, over an area where sinkholes have been experienced. Holes of 4m in diameter have developed, emanating from past mining activities at a depth of 30m.The design at Groebers consists of two elements:

   i.   injection of grout into known cavities

ii.   construction of a geosynthetic reinforced embankment which includes a basal warning system which will identify the nature and location of the development of any crown hole at the base of the embankment.

The embankment is constructed with two layers of geosynthetic grid reinforcement with a longitudinal strength of 1200 kN/m and a transverse strength of 100 kN/m.   The reinforcement is tensioned on laying.   The embankment itself is cement stabilized fill with a minimum thickness under the tracks of 2.95m.   The design has been subjected to a full scale trial, Ast *et al* (2001)

4.2   *France*

Full scale experiments have recently been conducted in France as part of the RAFAEL programmed (Reinforcement of Rail and Motorway Foundations against Localized Subsidence).   Road and rail tests have been conducted on a construction site of the new TGV Mediterranean high-speed train at Eurie in south east France.   Seven reinforced experimental cavities were created, three under the road and four under the rail track. Good agreement was achieved between the theoretical and experimental results.

A finding of the experiments was that geosynthetic reinforcement could only be used successfully with small diameter cavities when the width to height ratio of the cavity: embankment (D/H) was low.   With high ratios, limiting surface deformation to acceptable levels was difficult and remedial work involving filling of the resultant void was required before service could be resumed, Gourc *et al* (1999(a) and (b)).

4.3   *United Kingdom* Dolphingstone London-Edinburgh Main Line

In 2001 a number of sink holes appeared either side of the high speed Main East Coast Main Line (ECML) between London and Edinburgh. The cause of the voids, which measured up to 4m in diameter, was traced to old pillar and stall mine workings excavated in the 19th century. Subsidence from these workings had required remedial works over 100 years before and it was believed all movements had ceased. Mine records indicated that up to four seams had been worked at shallow depth with the seams out cropping adjacent to the track. The risk posed to the safety of the line was deemed to be very high with a potential risk to life. Immediate restrictions were introduced limiting track speeds to 30kph and studies under taken to resolve the problem.

The most effective solution in the minimum period was to realign the ECML over a distance of one mile (1600m). The new track passed over the area subject to subsidence and extensive remedial geotechnical works were under taken including extensive grouting. The new track was constructed on two reinforced concrete rafts supported on piles linked by a short section of embankment. The piles were driven through the zone containing the coal seams to sound rock. The embankment was reinforced with high strength geotextile similar to that used at Groebers near Liepzig. The cost of the diversion was £57m illustrating the scale of the problem posed by the subsidence.

5. Conclusion

Abandoned mine workings pose a serious threat to transportation systems. The most vulnerable are high speed rail networks were minor settlement of the track can result in major accidents and extensive disruption to the system. A major problem with abandoned mines is lack of knowledge of the extent of the problem and difficulty in predicting when and were it will occur. Until recently it was assumed that movements resulting from mine working under taken more than 100 years ago would be complete, but the recent cases of reactivation of subsidence is a major concern to rail operators. In the United Kingdom an extensive study is being under taken by Network Rail to permit management structures to be identified to resolve the problem.

8. References

Ast, W, Sobolewski, J and Habelard, J (2001) "Final design of an overbridging for railways endangered by cavities at Groebers" In Landmarks in Earth Reinforcement, Ochiai *et al* (eds.), pp.191-196, Swets & Zeitlinger, ISBN 902651 8633.

British Standards Institution (1995) "Code of Practice for Strengthened/Reinforced Soils and Other Fills" BS 8006, HMSO, London, 156.

CIRIA (1984) "Construction over abandoned mine workings" Special Publication No.32, CIRIA, London.

Gourc, J P and Villard, P (2000) "Reinforcement by membrane effect: application to embankments on soil liable to subsidence" Proc. of 2nd Asia Geosynthetics Conference, pp.55-72, Kuala Lumpur, Malaysia, May.

Gourc, J P, Villard, P, Giraud, H, Blivet, J C, Khay, M, Imbut, B, Horbois, A and Delmas, P L (1999a) "Sinkholes beneath a reinforced earth fill – a large scale motorway and railway experiment" Geosynthetics 99, Boston, IFAI.

Gourc, J P, Villard, P, Giraud, H, Blivet, J C, Khay, M, Imbut, B, Horbois, A and Delmas, P L (1999b) "Full scale experimentation of discontinuous subsidence for railway and motorway embankments" Proc. 12th European Conf. on Soil Mechanics and Geotechnical Engineering, Amsterdam.

Kempton, G T, Russell, D Piesport, N D and Jones, C J F P (1998) "Two- and three-dimensional numerical analysis of the performance of piled embankments" Proc. 6th Int. Conf. on Geosynthetics, Vol.2, pp.767-772, Atlanta, IFAI.

Lawson, C R (2001) "Earth reinforcement technique with geosynthetics in ASEAN region" In Geosynthetics and Earth Reinforcement, Ochiai, Otani and Miyata (eds.), ISSMGE, Technical Committee No.9, pp.10-23, ISSMGE-TC9.

Lawson, C R, Jones, C J F P and Kempton, G T (1996) "Some factors affecting the structural performance of reinforced fills spanning voids" In Earth Reinforcement, Ochiai, Yasufuku and Omine (eds.), pp.233-238, Balkema, ISBN 905410 8339.

Low, B K, Tang, S K and Choa, V (1994) "Arching in piled embankments" Journal of Geotechnical Engineering, ASCE, Vol.120, No.11, pp.1917-1938.

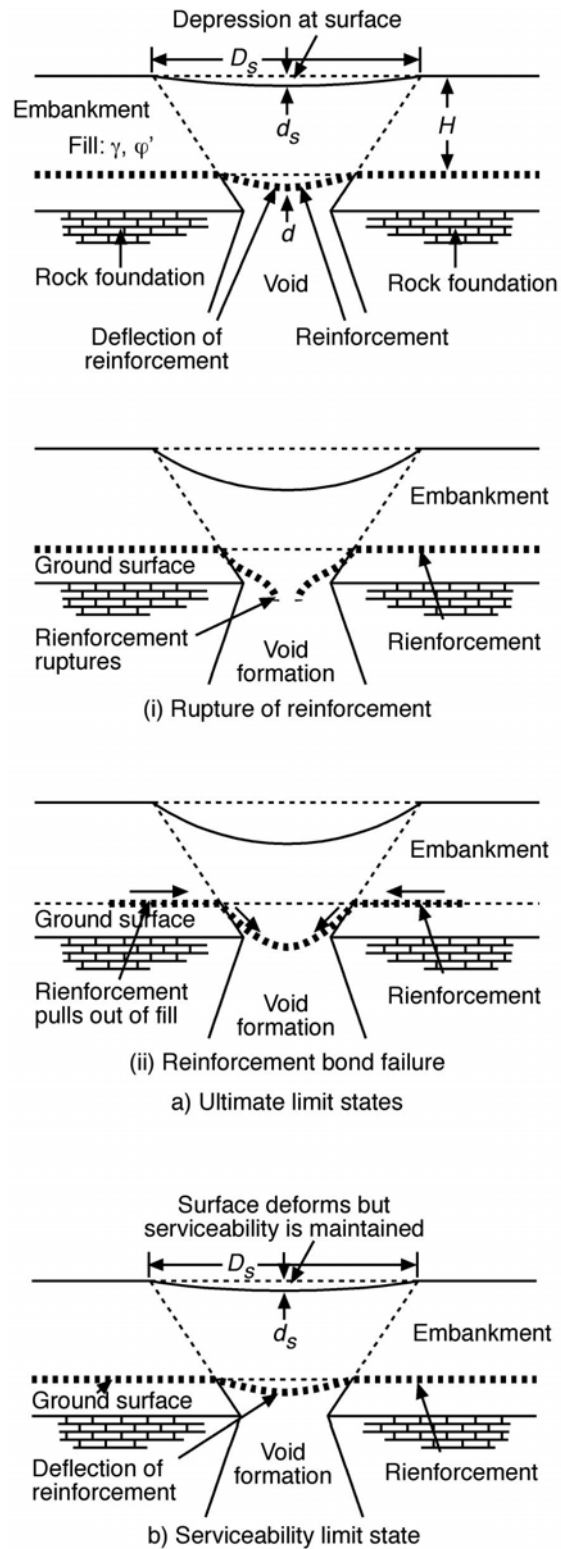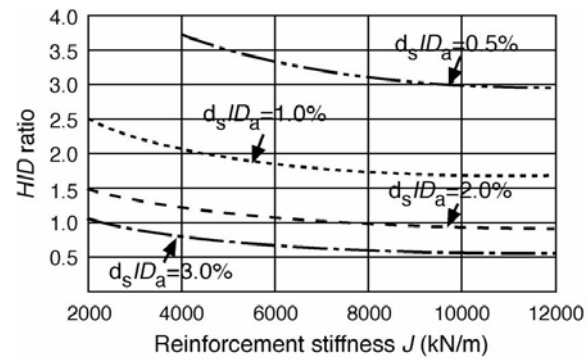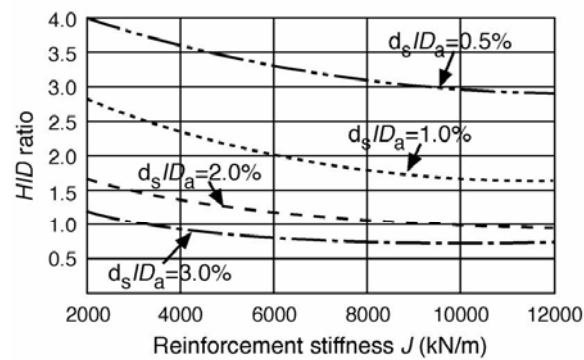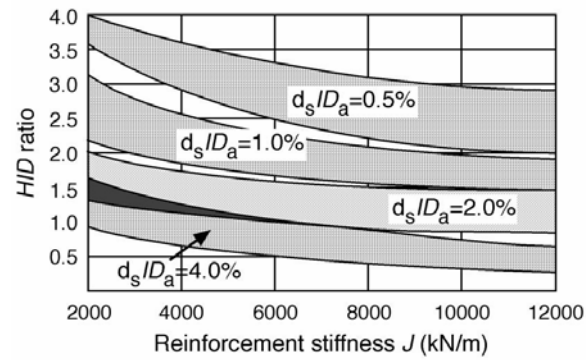Sims, F A, Bridle, J B (1996) "Bridge design in areas of mining subsidence" Jour. Inst. High. Eng. Pp 19-34 Nov.

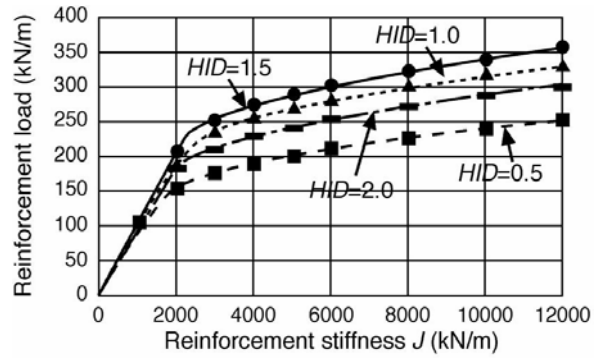Figure 1: Basal reinforced embankments spanning voids

a) For void diameter D=1m
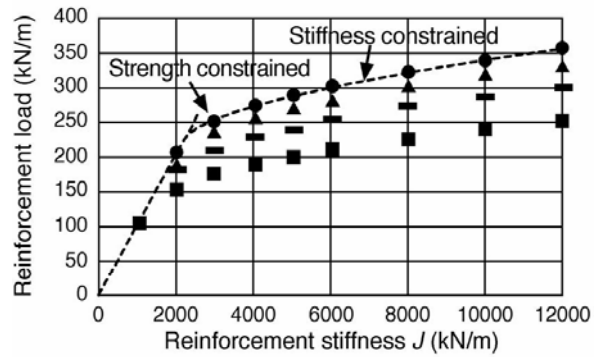

b) For void diameter D=4m

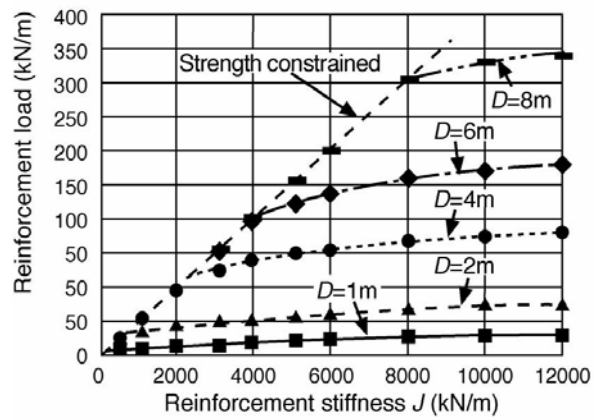c) For all void diameters less than or equal to 8m

Figure 2: Effect of reinforcement stiffness on reinforcement load for different ratios of H/D and void diameter

a) Load in reinforcement for void diameter D = 4m

b) Strength and stiffness constrained regions at HID=1.5 for void diameter D=4m

c) Reinforcement load versus stiffness at HID=1.5 for void diameters D≤8m

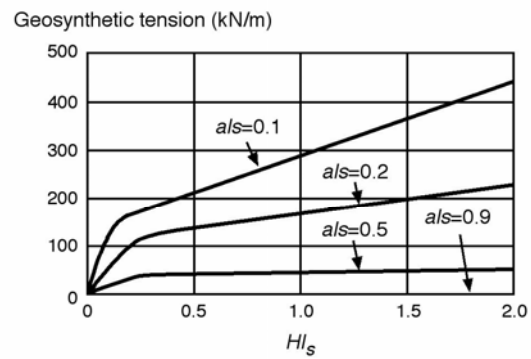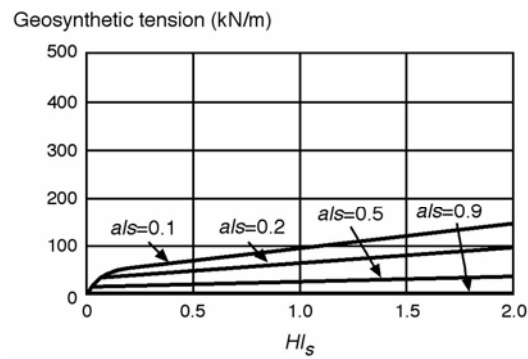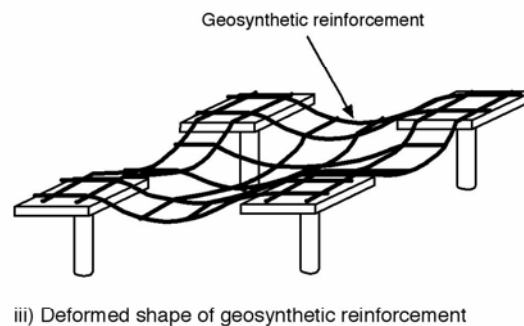Figure 3: Effect of reinforcement stiffness on reinforcement load
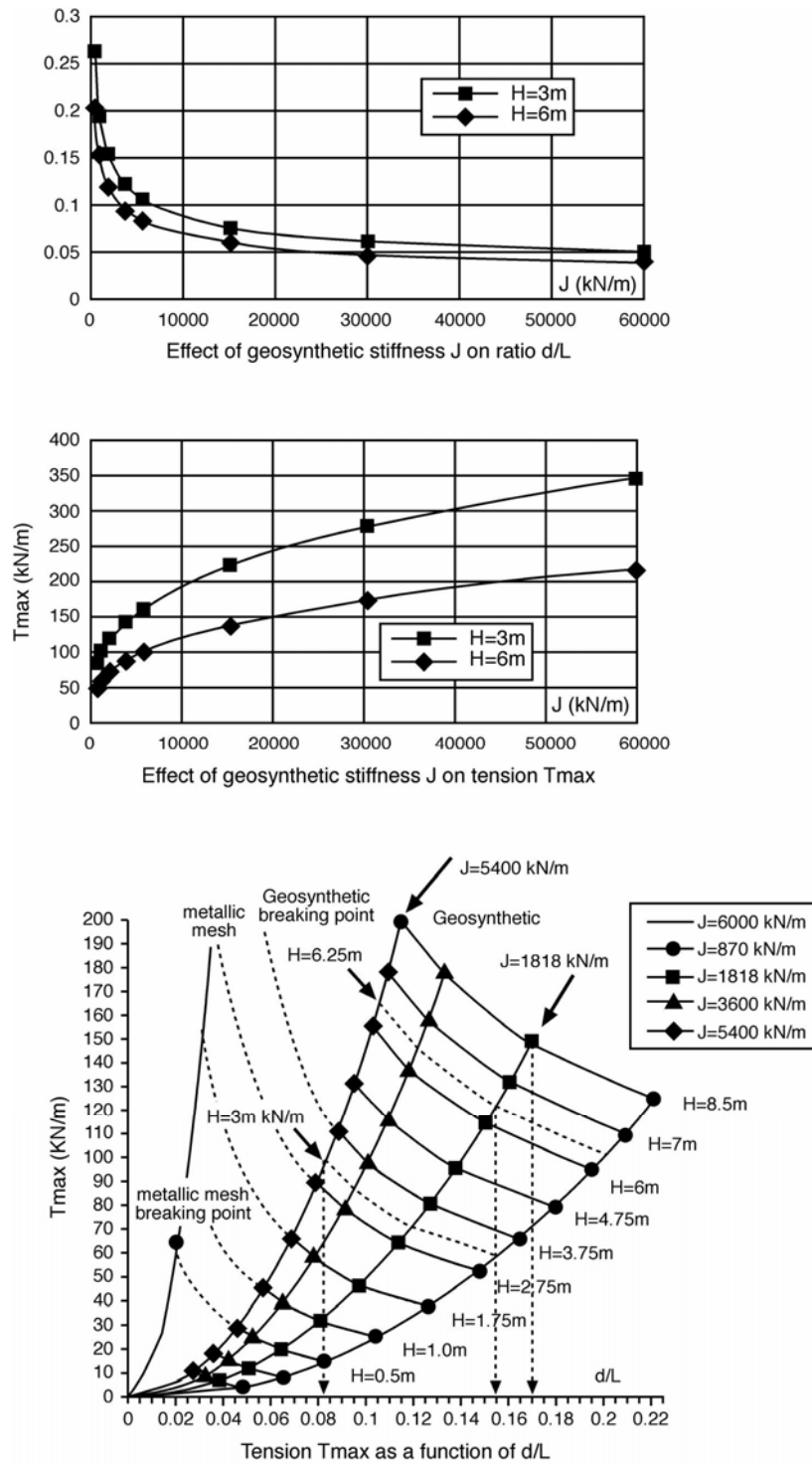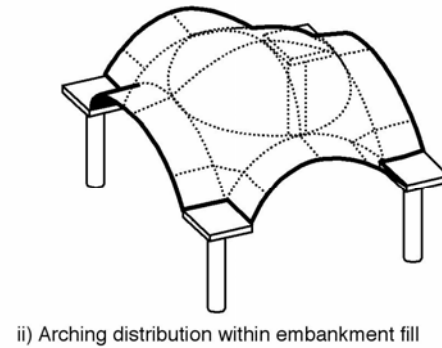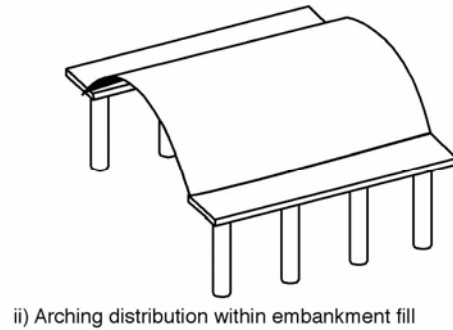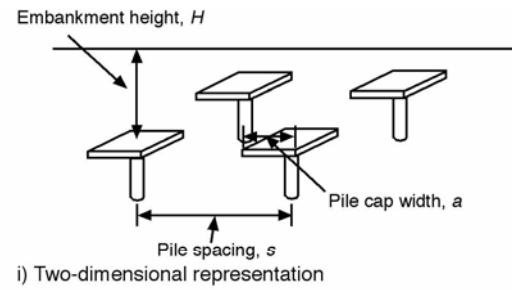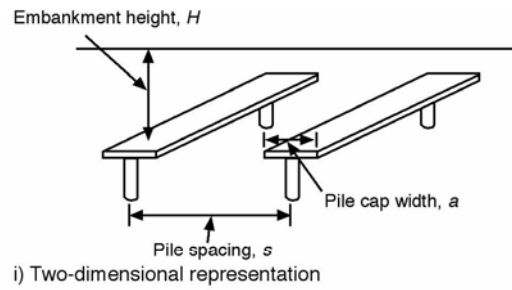
Figure 4: Relationship between maximum tension and the ratio of the deflection of the reinforcement (d) to the diameter of the crown hole (L)

Embankment height, *H*

Pile cap width, *a*

Pile spacing, *s*

i) Two-dimensional representation

ii) Arching distribution within embankment fill

Geosynthetic reinforcement

iii) Deformed shape of geosynthetic reinforcement

Geosynthetic tension (kN/m)

a/s=0.1 *a/s*=0.2 *a/s*=0.5 *a/s*=0.9

H/s

iv) Geosynthetic tension (After Kempton et al. 1998)

a) Two-dimensional case

Embankment height, *H*

Pile cap width, *a*

Pile spacing, *s*

i) Two-dimensional representation

ii) Arching distribution within embankment fill

Geosynthetic reinforcement

iii) Deformed shape of geosynthetic reinforcement

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a/s=0.1 *a/s*=0.2 *a/s*=0.5 *a/s*=0.9

H/s

iv) Geosynthetic tension (After Kempton et al. 1998)

b) Three-dimensional case

Figure 5: The analytical models of piled embankments